Spectroscopic properties and laser performance of resonantly-pumped cryo-cooled Er^{3+}:$GdVO_4$

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Abstract: We report a highly efficient cryo-cooled eye-safe laser operation of a resonantly-pumped (in-band) Er^{3+}:$GdVO_4$ single crystal. The maximum continuous wave (CW) power of 10.3 W with 84% slope efficiency was achieved at 1598.7 with pumping at 1538.6 nm by a spectrally-narrowed Er-fiber laser. Under the 1529 nm resonant pumping by a commercially available diode bar stack operating in a quasi-CW (QCW) mode, the laser delivered 37 W of output power with 68% slope efficiency. This is believed to be the first reported cryo-cooled Er^{3+}:$GdVO_4$ laser, resonantly-pumped into the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid-state; (140.3500) Lasers, erbium.

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14. ABSTRACT
We report a highly efficient cryo-cooled eye-safe laser operation of a resonantly-pumped (in-band) Er3+:GdVO4 single crystal. The maximum continuous wave (CW) power of 10.3 W with 84% slope efficiency was achieved at 1598.7 with pumping at 1538.6 nm by a spectrally-narrowed Er-fiber laser. Under the 1529 nm resonant pumping by a commercially available diode bar stack operating in a quasi-CW (QCW) mode, the laser delivered 37 W of output power with 68% slope efficiency. This is believed to be the first reported cryo-cooled Er3+:GdVO4 laser resonantly-pumped into the 4I15/2 →4I13/2 transition.

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1. Introduction

Er-doped laser materials have been established as one of the best choices in designing resonantly-pumped, highly scalable eye-safe lasers operating in the 1.6 micrometer (μm) wavelength range. Cryogenically-cooled, Er-doped lasers such as Er:YAG, Er:YVO_4, Er:Sc_2O_3 and Er:NaY$(WO_4)_2$, have demonstrated very efficient low quantum defect (QD) operation [1–5]. Cryogenic cooling is known to improve thermo-mechanical, thermo-optical, and spectroscopic properties for the majority of laser hosts. While absorption and emission cross-sections become stronger with cooling, the absorption lines also become much narrower and require narrow-linewidth pump sources – the issue which can hinder pumping efficiency [6]. Disordered laser hosts, such as Er:NaY$(WO_4)_2$, even at cryogenic temperatures exhibit very broad absorption transitions convenient for resonant pumping, but their thermal conductivity is usually low, which limits power scaling [3]. Uniaxial Erbium-doped yttrium vanadate material (Er:YVO_4) offers a compromise: it exhibits large absorption and emission cross-sections while its absorption lines remain relatively broad. This feature helps in achieving efficient laser operation with InP diode-based pump sources [4]. Similarly high efficiency can potentially be expected for Er:$GdVO_4$ laser (which is a close analog to Er:YVO_4).

Rare earth-doped gadolinium vanadate ($GdVO_4$) was introduced in 1992 [7] as a close analog to commercially available YVO_4. Additional interest to $GdVO_4$ is also driven by contradictory literature data on its thermal conductivity relative to that of YAG and especially of YVO_4 [8–10]. Most of the latest reported data indicates that the thermal conductivity of $GdVO_4$ along its crystallographic c-axis is higher than that of YAG and at least similar to that of YVO_4. While efficient resonantly-pumped cryogenic and room temperature Er:YVO_4 lasers have been reported earlier [4, 5, 11, 12], the laser potential of the similarly pumped Er^{3+}:$GdVO_4$, to the best of our knowledge, has only been evaluated at room temperature [13]. The maximum CW output power of 3.5 W with slope efficiency of 56% was achieved with resonant pumping by an Er-fiber laser at 1538.6 nm. With pumping by a commercial diode laser bar stack, a quasi-CW (QCW) output of 7.7 W and a maximum slope efficiency of ~53% with respect to the absorbed pump power were obtained [13].

In this paper, we present spectroscopic characteristics of Er^{3+}:$GdVO_4$ in the 1450–1650 nm wavelength range defined by the $^4I_{13/2} \leftrightarrow {}^4I_{15/2}$ transitions and report the laser performance of a cryo-cooled Er^{3+}:$GdVO_4$ crystal under the resonant pumping by two different pump sources: spectrally-narrow Er-fiber laser and commercial InGaAsP/InP diode bar stack. The maximum CW power of 10.3 W with 84% slope efficiency was achieved at 1598.7 nm with pumping at 1538.6 nm by a fiber laser. Under the 1529 nm resonant pumping by a diode bar stack operating in a QCW mode, the laser delivered 37 W of output power with 68% slope efficiency. To the best of our knowledge, this is the first resonantly-pumped cryo-cooled laser based on $^4I_{13/2} \leftrightarrow {}^4I_{15/2}$ transitions of Er^{3+} in $GdVO_4$.

2. Spectroscopy

For spectroscopic characterization, we used an Er^{3+}:$GdVO_4$ crystal grown by the Czochralski technique with a doping concentration of 0.5% (N_{Er} = $6.05 \cdot 10^{19}$ cm^{-3}). The measurements were focused on the $^4I_{13/2} \leftrightarrow {}^4I_{15/2}$ transitions within the 1450–1650 nm wavelength range.

The polarization-resolved absorption spectra of the Er^{3+}:$GdVO_4$ crystal, cryogenically-cooled to 77 K, were measured using Cary 6000i spectrophotometer, operating in the fixed-slit-width mode with the 0.1 nm resolution. The cross-sections of Er^{3+}:$GdVO_4$, derived from the measured absorbance, are presented in Fig. 1(a). The absorption bands are generally stronger for σ-polarization, with the exception of a broad and strong transition at ~1502 nm (cross-section σ_{abs} ~$2.2 \cdot 10^{-19}$ cm^2). The zero-zero absorption line at 1529.3 nm, which corresponds to the transition from the lowest Stark components of the $^4I_{15/2}$ and the $^4I_{13/2}$ manifolds, also exhibits a large cross-section of ~1.5-1.6·10^{-19} cm^2. This transition has approximately equal strength for both polarizations with the linewidth of ~1.3 nm full width half maximum (FWHM) and, thus, is suitable for pumping by an unpolarized source.

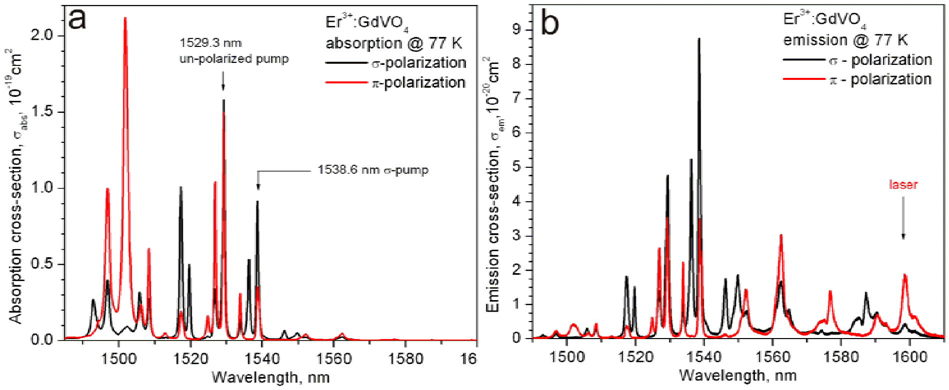

Fig. 1. Polarization resolved absorption (a) and emission (b) cross-sections of the $^4I_{15/2} \leftrightarrow {}^4I_{13/2}$ transitions in Er^{3+}:$GdVO_4$.

The emission spectra of Er^{3+}:$GdVO_4$ sample were obtained by exciting the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ fluorescence with a 970 nm diode laser (via $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition). Luminescence was collected and processed by an optical spectrum analyzer (Yokogawa, model AQ6370C) with spectral resolution set to 0.02 nm. A polarization beam splitter was inserted into collecting optics to separate the σ- and π-polarized signals. Cross-sections ($\sigma_{\rm emi}$) of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions in both polarizations, calculated using the standard Fuchtbauer-Landenburg method [14], are shown in Fig. 1(b).

The π-polarized emission exhibits a major peak around 1599 nm ($\sigma_{\rm emi}$ ~2·10^{-20} cm^2), formed by the two overlapping transitions centered at ~1598.7 ($Y_1 \rightarrow Z_7$) and at ~1599 nm ($Y_2 \rightarrow Z_8$). In the σ-polarized spectrum, there is an attractive peak around 1588 nm with $\sigma_{\rm emi}$ ~1.3·10^{-20} cm^2. This peak is also formed by two almost indistinguishable (wavelength-wise) transitions: $Y_1 \rightarrow Z_6$ and $Y_3 \rightarrow Z_7$.

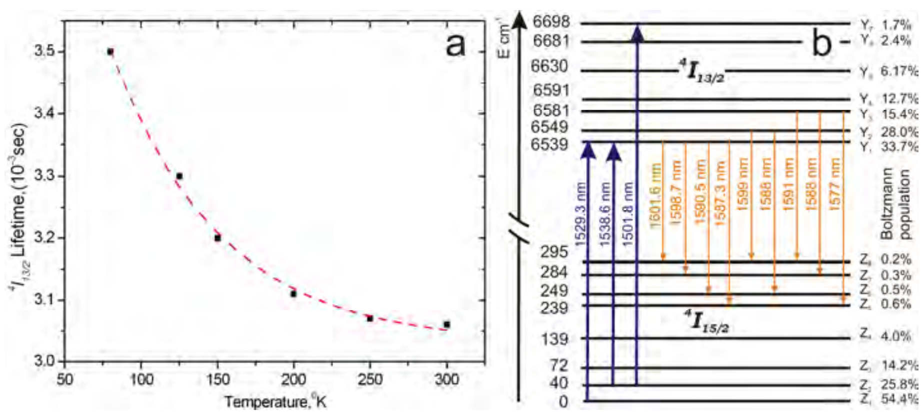

Fig. 2. (a) Temperature dependence of the $^4I_{13/2}$ lifetime of Er^{3+} in $GdVO_4$. (b) A simplified energy level diagram of the $^4I_{13/2}$ and the $^4I_{15/2}$ manifolds with Boltzmann populations at 77 K. The major pump transitions are shown with blue arrows; red arrows represent the fluorescence transitions of relevance to laser operation around 1.6 µm.

The fluorescence lifetime of the $^4I_{13/2}$ level was measured on a 0.5%-doped Er^{3+}:$GdVO_4$ crystal sample, which was pulverized in order to minimize effects of reabsorption and radiation trapping on experimental results. The sample was excited by 100 μsec pulses of an InP diode laser tuned to the 1529 nm absorption line. The fluorescence signal was detected with a Germanium photodiode and the sampled kinetic was processed by a digital oscilloscope (Tektronix, model TDS 2022B). A room temperature lifetime was measured to be ~3.06 ms and versus ~3.5 ms measured at 77 K. The results for the entire temperature range of 77-300K, presented in Fig. 2(a), were consistent with those measured by ***Bertini et al*** for a 1% Er:$GdVO_4$ sample [15].

The simplified energy level diagram of the Er^{3+}:$GdVO_4$ crystal for the $^4I_{13/2}$ and the $^4I_{15/2}$ manifolds obtained from the analysis of the absorption and emission spectra and major transitions between their Stark sublevels are shown in Fig. 2(b). This diagram is also consistent with that reported by ***Bertini et al*** [15].

3. Cryogenic laser experiments

Laser experiments were carried out on an anti-reflection coated 10 mm long, 7 mm wide, and 3 mm thick Er^{3+}(0.7%):$GdVO_4$ single crystal (N_{Er} = 8.47·10^{19} cm^{-3}). Its crystallographic ***c***-axis was normal to the axis of the laser cavity, thus, the crystal could be longitudinally pumped in any chosen polarization. The crystal was mounted on a copper plate inside the liquid nitrogen cryostat. The setup was almost identical to that described in [4].

Two different pump sources spectrally matching one of the major absorption lines of Er^{3+}:$GdVO_4$ were used in laser experiments. One of them was a 20 W, CW, unpolarized, single mode Er-fiber laser with a ~0.3 nm FWHM emission bandwidth, which fits inside the 1538.6 nm absorption line. The motivation for using a narrow-linewidth, single mode fiber laser as a pump source was to avoid both spectral and spatial mismatches in pumping in order to achieve maximum efficiency of the Er^{3+}:$GdVO_4$ laser in a low QD operation.

The pump beam was focused into the crystal by the F = 100 mm spherical lens through a flat dichroic mirror (T > 98% @ 1520 −1540 nm, R > 99.5% @ 1590 −1650 nm). The pumped volume was cylindrical in shape with a diameter of ~330 μm (at 1/e^2 level) along the entire crystal length, as measured by IR CCD camera (Spiricon, model LW230).

The laser cavity was formed by the flat dichroic mirror and a concave output coupler with the radius of curvature (R_{CC}) of 100 mm and reflectivities (R_{OC}) within the 70% - 90% range. The cavity length (L_{cav}) was chosen to be about 80 mm to provide the best pump-cavity mode spatial matching.

The CW performance of the cryogenic Er^{3+}:$GdVO_4$ laser, resonantly pumped into the 1538.6 nm absorption line by the Er-fiber laser, is shown in Fig. 3(a). Without any wavelength selective elements inside the cavity, the laser operated in π-polarization at 1598.7 nm with 3.9% QD. The emission bandwidth strongly depended on the pump power and its full value approached 4 nm at the maximum pump.

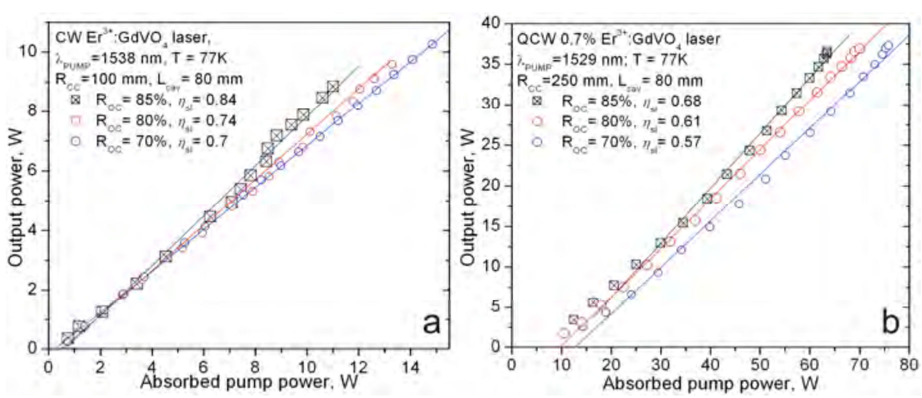

Fig. 3. Input-Output characteristics of the cryogenic Er^{3+}:$GdVO_4$ laser. (a) CW pumping with the Er-fiber laser; (b) Pumping with the QCW diode bar stack.

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The fraction of the absorbed pump varied due to the saturation effect [16] from ~0.85 at the threshold to ~0.65 at full 20 W of the incident pump and was predictably dependent on the output coupling. In order to avoid inconsistencies in laser efficiency measurement, we determined the absorbed pump when the laser was in the "operational" mode (above the threshold), measuring the incident pump, the transmitted pump and the laser output power simultaneously.

As seen in Fig. 3(a), the maximum achieved slope efficiency was 84% with R_{OC} = 85%. The maximum obtained CW output power was 10.3 W for the R_{OC} = 70%.

The second pump source was a commercial spectrally narrowed (~2 nm FWHM), both fast- and slow-axis collimated (FAC/SAC), InGaAsP/InP 13-bar diode laser stack, rated at 1532 nm (QPC Lasers). This source is much more relevant for practical laser designs, which was a motivation for this part of the study. In our experiments, it was operated in a quasi-CW regime with a 5% duty cycle (τ_{pulse} = 10 ms). The incident pump beam was π-polarized and its wavelength was temperature-tuned to the absorption band around 1529 nm by varying the coolant temperature of the stack. In order to nearly equalize the divergence of the pump beam in the vertical and the horizontal directions, an additional 4^X cylindrical telescope was placed after the diode stack. A variable pump attenuator, consisting of a polarizing cube and a half-wave plate, was inserted between the telescope and the stack. This setup allowed us to maintain a constant pumping wavelength while varying the pump power. The collimated pump beam was focused into the crystal by a spherical lens (F = 75 mm) through the same flat dichroic mirror used in the previous experiment. This time, the pump formed a cone inside the crystal with the $1/e^2$ diameter varying from 960 μm in the center to approximately 1200 μm at the crystal ends.

As in the previous case, the laser cavity was formed by the dichroic high reflector and a concave output coupler with R_{OC} varying from 90% to 70%. This time, however, in order to accommodate a larger pump mode and to achieve a better pump-cavity mode matching, the radius of curvature was chosen to be 250 mm with the L_{cav} = 80 mm.

Figure 3(b) shows the QCW performance of the Er^{3+}:$GdVO_4$ laser with the laser diode stack pumping. It also operated in a π-polarization at 1598.7 nm (4.6% QD). The best slope efficiency of 68% was achieved with the R_{OC} = 85%. The maximum obtained QCW laser output was 37.3 W. The fraction of the QCW absorbed pump varied from 0.73 - 0.83 at the threshold to 0.66-0.77 at full 96 W of the pump power (for R_{OC} = 85% and 70% respectively). The difference in efficiencies of fiber laser- and the diode bar stack-pumped Er:$GdVO_4$ lasers can be explained by much better pump-cavity mode matching in the former case.

4. Conclusions

We reported what is believed to be the first resonantly-pumped cryo-cooled laser based on an Er^{3+} doped $GdVO_4$ single crystal. Spectroscopic characteristics and laser performance of this laser utilizing transitions between the ${}^4I_{15/2}$ and ${}^4I_{13/2}$ manifolds (1450-1650 nm) at cryogenic temperatures were investigated. A slope efficiency as high as 84% and a maximum CW output power of 10.3 W at 1598.7 nm have been obtained for resonant pumping into the 1538.6 nm absorption line by a narrow-linewidth Er-fiber laser. With the resonant pumping into the 1529 nm absorption band by a commercial InGaAsP/InP FAC/SAC laser diode bar stack, we achieved the maximum slope efficiency of ~68% and the maximum QCW output power of ~37 W.

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